CP Violation and the Origin of Matter:

What can the linear collider teach us?

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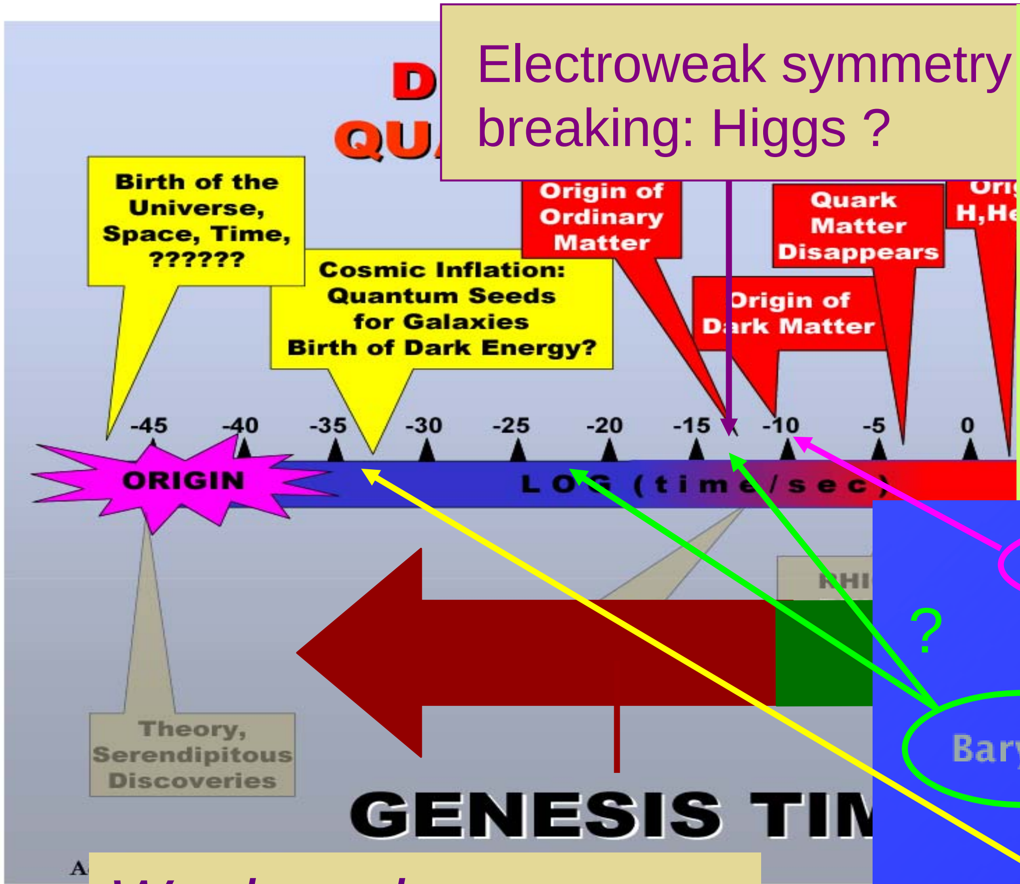
PRD 71: 075010 (2005)
PRD 73: 115009 (2006)
JHEP 0607: 002 (2006)

The Origin of Matter & Energy



Electroweak symmetry breaking: Higgs ?

Baryogenesis: When? SUSY? Neutrinos? CPV?

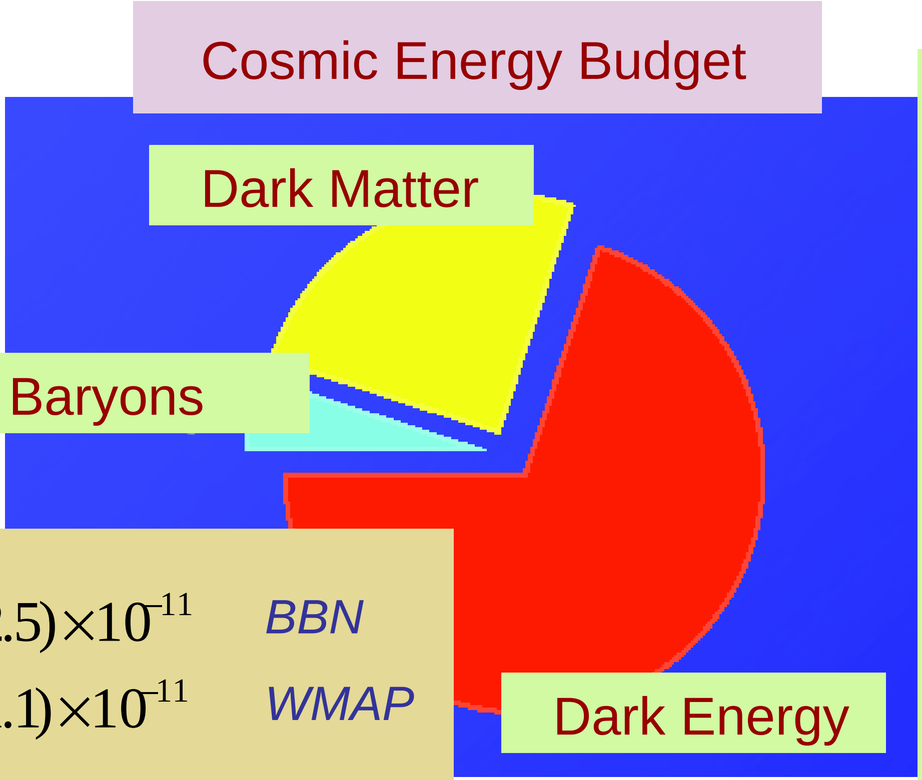
WIMPy D.M.: Related to baryogenesis?

"New gravity"? Grav baryogenesis ?

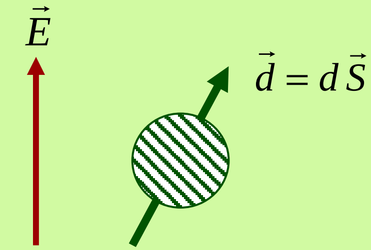
Cosmic Energy Budget

Weak scale baryogenesis can be tested experimentally

What is the origin of baryonic matter ?



$$Y_B = \frac{\rho_B}{s_\gamma} = \begin{cases}(7.3\pm 2.5)\times 10^{-11} & \text{BBN} \\ (9.2\pm 1.1)\times 10^{-11} & \text{WMAP}\end{cases}$$



$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$

T-odd , CP-odd
by CPT theorem

What complementary information is needed from collider studies, precision electroweak measurements, and dark matter searches ?

EDM Probes of New CP Violation

CKM → d_{SM}

f	d_{SM}	d_{exp}	d_{future}
e^-	$< 10^{-40}$	$< 1.6\times10^{-27}$	$\rightarrow 10^{-31}$
n	$< 10^{-30}$	$< 6.3\times10^{-26}$	$\rightarrow 10^{-29}$
^{199}Hg	$< 10^{-33}$	$< 2.1\times10^{-28}$	$\rightarrow 10^{-32}$
μ	$< 10^{-28}$	$< 1.1\times10^{-18}$	$\rightarrow 10^{-24}$

Also ^{225}Ra, ^{129}Xe, d

If new EWK CP violation is responsible for abundance of matter, will these experiments see an EDM?

EW Baryogenesis: Standard Model

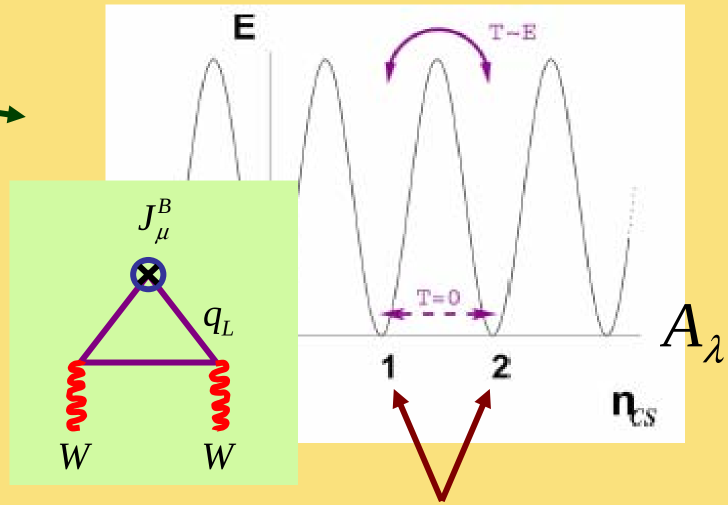
Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics

Sakharov, 1967

Kuzmin, Rubakov, Shaposhnikov McLerran,…

Anomalous Processes



Different vacua: $\Delta(B+L) = \Delta N_{CS}$

Sphaleron Transitions

EW Baryogenesis: Standard Model

Shaposhnikov

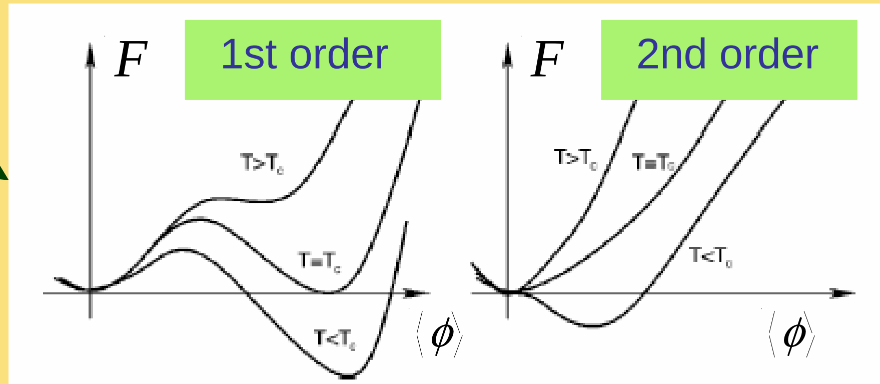
Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics

Sakharov, 1967

$$J = s_{12}\, s_{13}\, s_{23}\, c_{12}\, c_{13}^{2}\, c_{23} \sin \delta_{13}$$
$$= (2.88 \pm 0.33) \times 10^{-5}$$

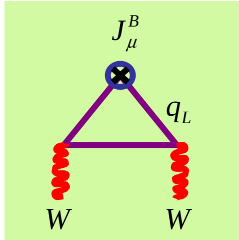
$$\frac{m_t^4}{M_W^4}\,\frac{m_b^4}{M_W^4}\,\frac{m_c^2}{M_W^2}\,\frac{m_s^2}{M_W^2} \approx 3\times10^{-13}$$



Increasing m_h →

- CP-violation too weak
- EW PT too weak

Baryogenesis: New Electroweak Physics

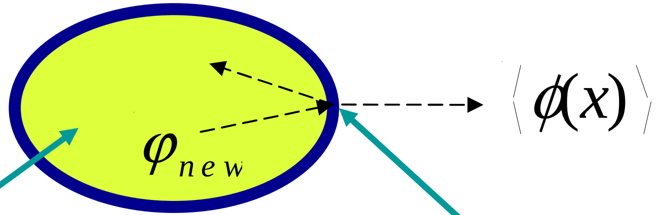


Unbroken phase

Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics

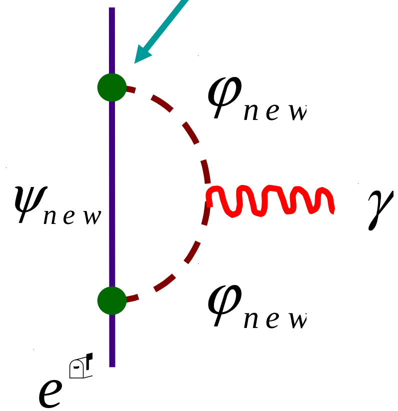
Topological transitions



Broken phase

CP Violation

1st order phase transition



Theoretical Issues:

Transport at phase boundary (non-eq QFT)

Bubble dynamics (numerical)

Strength of phase transition (beyond MSSM)

EDMs: many-body physics & QCD

New Developments

Quantum Transport Dynamics:

Application of non-equilibrium QFT techniques: systematic analysis, detailed parameter dependence, theoretical uncertainties

Riotto, Carena et al, Lee et al, Konstandin et al

Coupling with Dark Matter

Carena et al, Profumo et al, Konstandin et al…

Electroweak Symmetry Breaking

Extended Higgs sector models

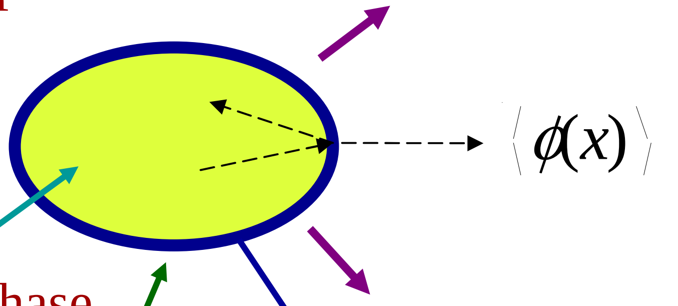
Barger et al, Carena et al, Konstandin et al…

Systematic Baryogenesis

Cohen, Kaplan, Nelson
Joyce, Prokopec, Turok

Unbroken phase

Topological transitions



"snow"

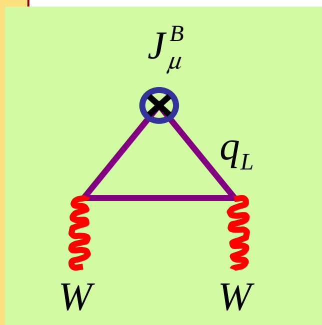
Broken phase

1st order phase transition

n_L produced in wall & diffuses in front

$$\frac{\partial\rho_B}{\partial t} - D\nabla^2\rho_B = -\Gamma_{WS}\, F_{WS}(x)\left[n_L(x) + R\rho_B\right]$$

F_{WS} (x) !0 deep inside bubble

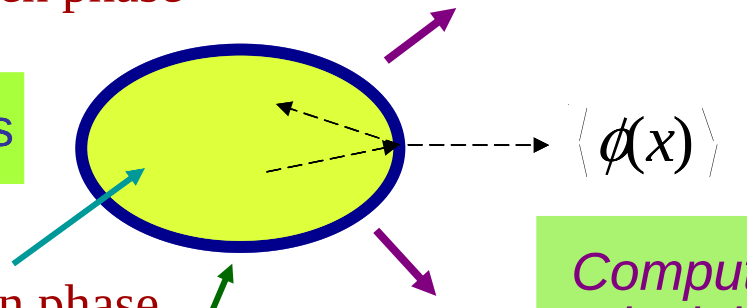


Systematic Baryogenesis

Riotto
Carena et al
Lee, Cirigliano, Tulin, R-M
Konstandin et al

Unbroken phase

Topological transitions

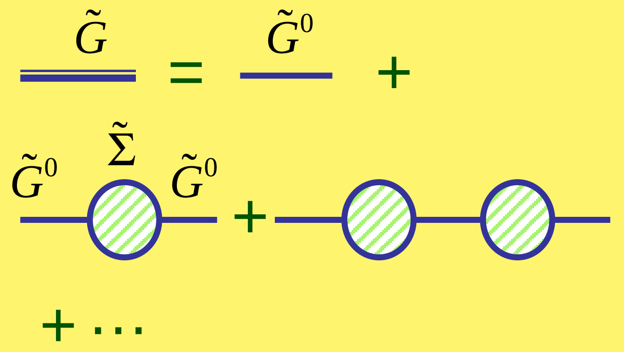


Broken phase

1st order phase transition

Compute from first principles given $\mathcal{L}_{new}$

$$\frac{\partial n_i}{\partial t} - D\nabla^2 n_i = S\left(n_j, T, \varphi, \tilde{M}\right)$$



Quantum Transport Equation

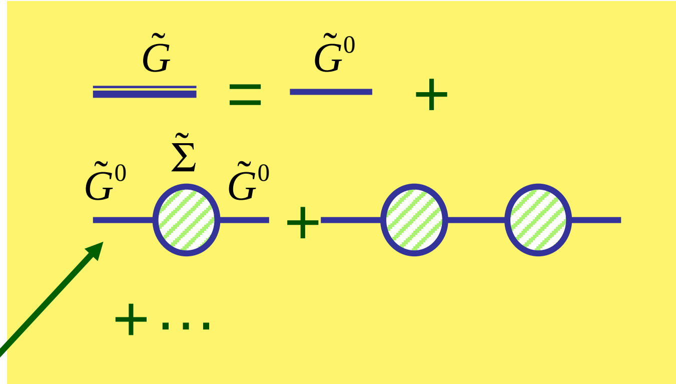
Schwinger-Dyson Equations

Systematic Baryogenesis

Departure from equilibrium

- *Non-adiabatic evolution of states & degeneracies*

$$_{out}\langle 0| = \ _{in}\langle 0|S^{\dagger} \neq e^{i\alpha}\left(_{in}\langle 0|\right)$$



Generalized Green's Functions: Closed Time Path

- *Non-thermal distributions*

Exploit scale hierarchy: expand in scale ratios ε

$$f_i(E) = f_0(E, \mu_i, T) + \varepsilon f'(E) + \cdots$$

Quantum Transport Equations

$$\partial_X^{\mu} j_{\mu}(X) = \int d^3z \int_{-\infty}^{X_0} dz_0 \left[\Sigma^{>}(X,z) G^{<}(z,X) - G^{>}(X,z) \Sigma^{<}(z,X) + \cdots \right]$$

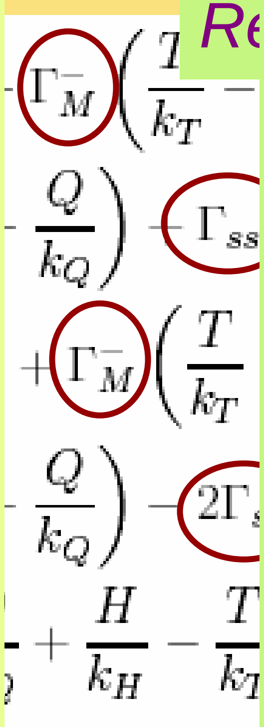
Expand

Approximations

- neglect $O(\varepsilon^3)$ terms

Ch

Re



From S-D Equations:

- S^{CPV}

Riotto, Carena et al, Lee et al

- Γ_M , Γ_H , Γ_Y

Lee et al

Numerical work:

- Γ_{SS}

violation i

and baryon sectors

Currents

Phenomenology: MSSM (Illustrative)

Baryon Number

$$Y_B = \frac{\rho_B}{s_\gamma} = F_1 \sin\phi_\mu + F_2 \sin(\phi_\mu + \phi_A)$$

$$F_1 \propto \frac{S_{\tilde{H}}^{CPV}}{\sqrt{\overline{\overline{\Gamma}}}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

Higgsinos

$$F_2 \propto \frac{S_{\tilde{t}}^{CPV}}{\sqrt{\overline{\overline{\Gamma}}}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

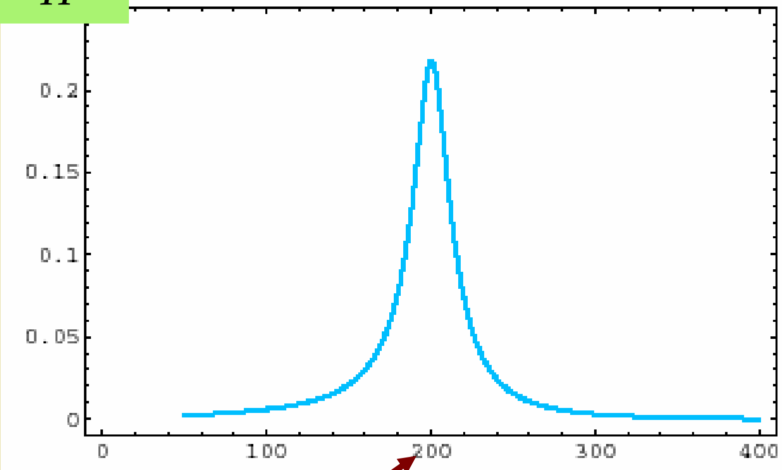
Squarks

MSSM EWB: Higgsino-Gaugino driven

Resonant CPV & Relaxation

$\hat{S}_{\tilde{H}}$

CP violation



$M_{\tilde{W}}$

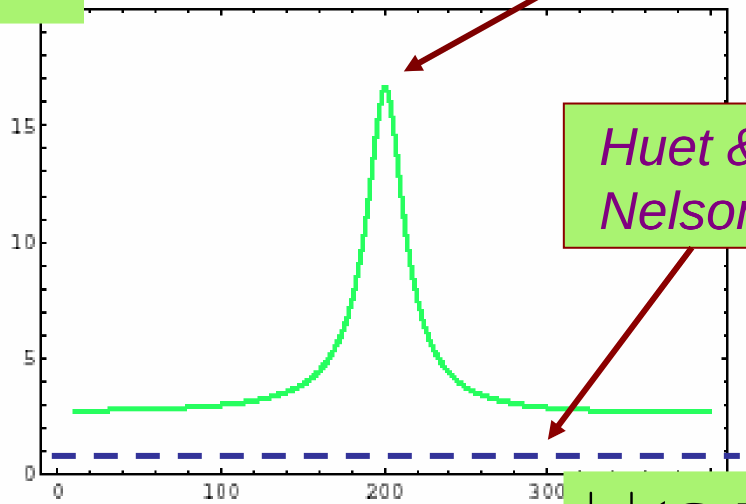
$|\mu|$ (GeV)

R_{Γ}

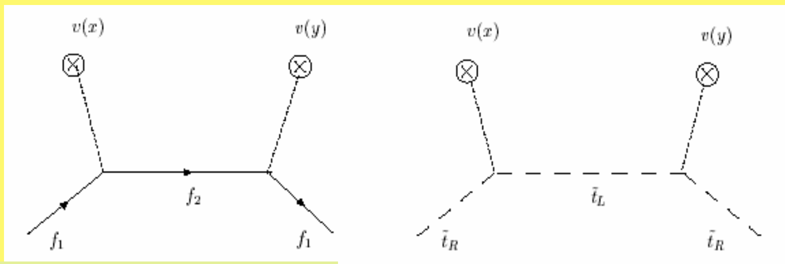
Relaxation

$M_{\tilde{W}}$

Huet & Nelson



$|\mu|$ (GeV)

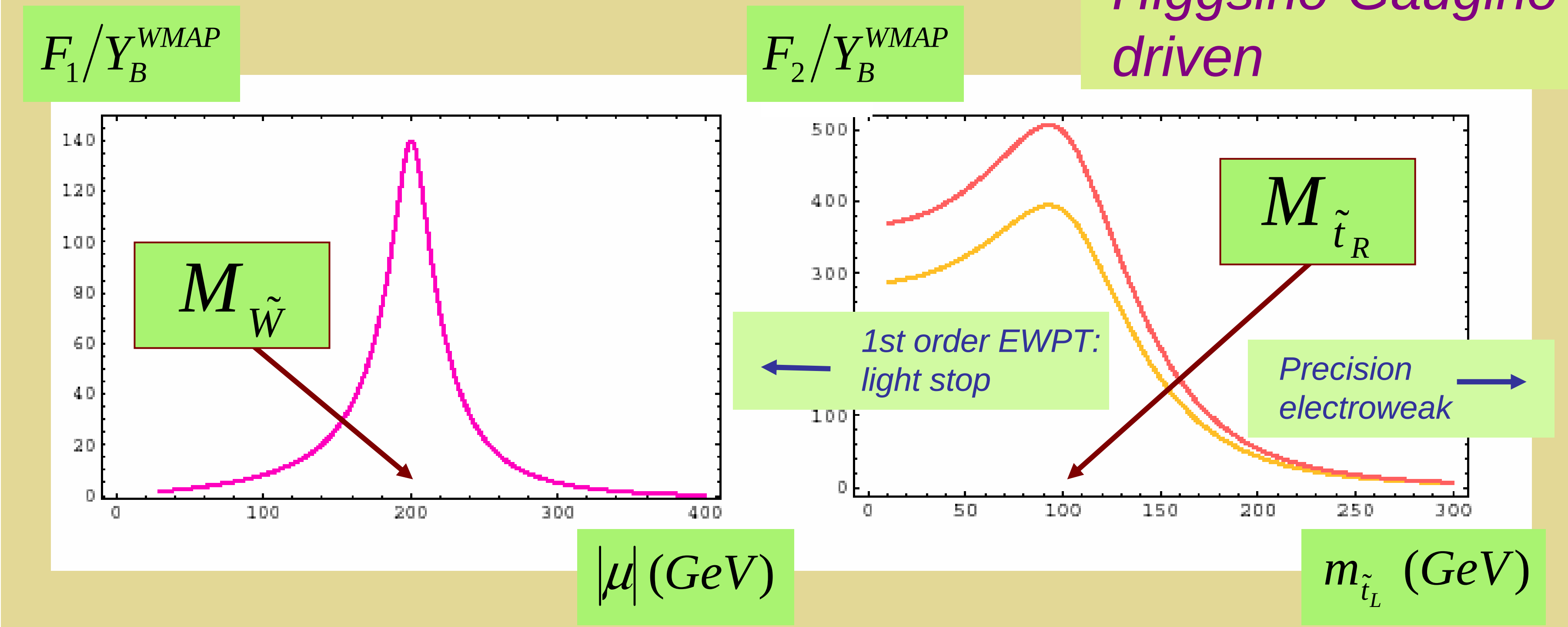


$\tilde{H} \leftrightarrow \tilde{W}$

$$F_1 \propto \frac{S^{CPV}_{\tilde{H}}}{\sqrt{\bar{\Gamma}}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

Resonant CPV & Relaxation

MSSM EWB: Higgsino-Gaugino driven

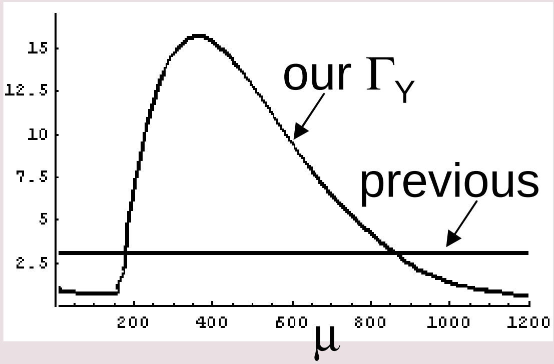


$$Y_B = \frac{\rho_B}{s_\gamma} = F_1 \sin\phi_\mu + F_2 \sin(\phi_\mu + \phi_A)$$

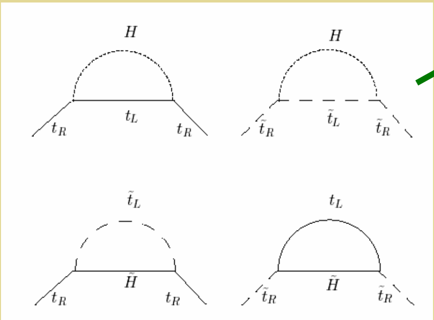
$$F_2/F_1 \sim 10^{-3}$$

Baryon Number & Γ_Y

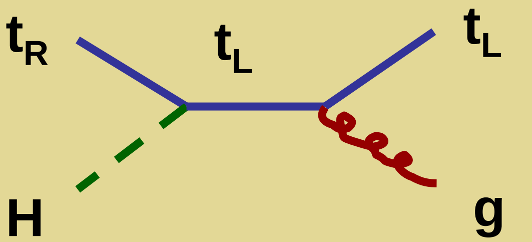
$$Y_B = \frac{\rho_B}{s_\gamma} = F_1 \sin\phi_\mu + F_2 \sin(\phi$$



$$F_i = F_i^{\infty}\left[1 + \Delta\left(\frac{\Gamma_H}{\Gamma_Y}\right)\right]$$



$O(\alpha_s^0)$



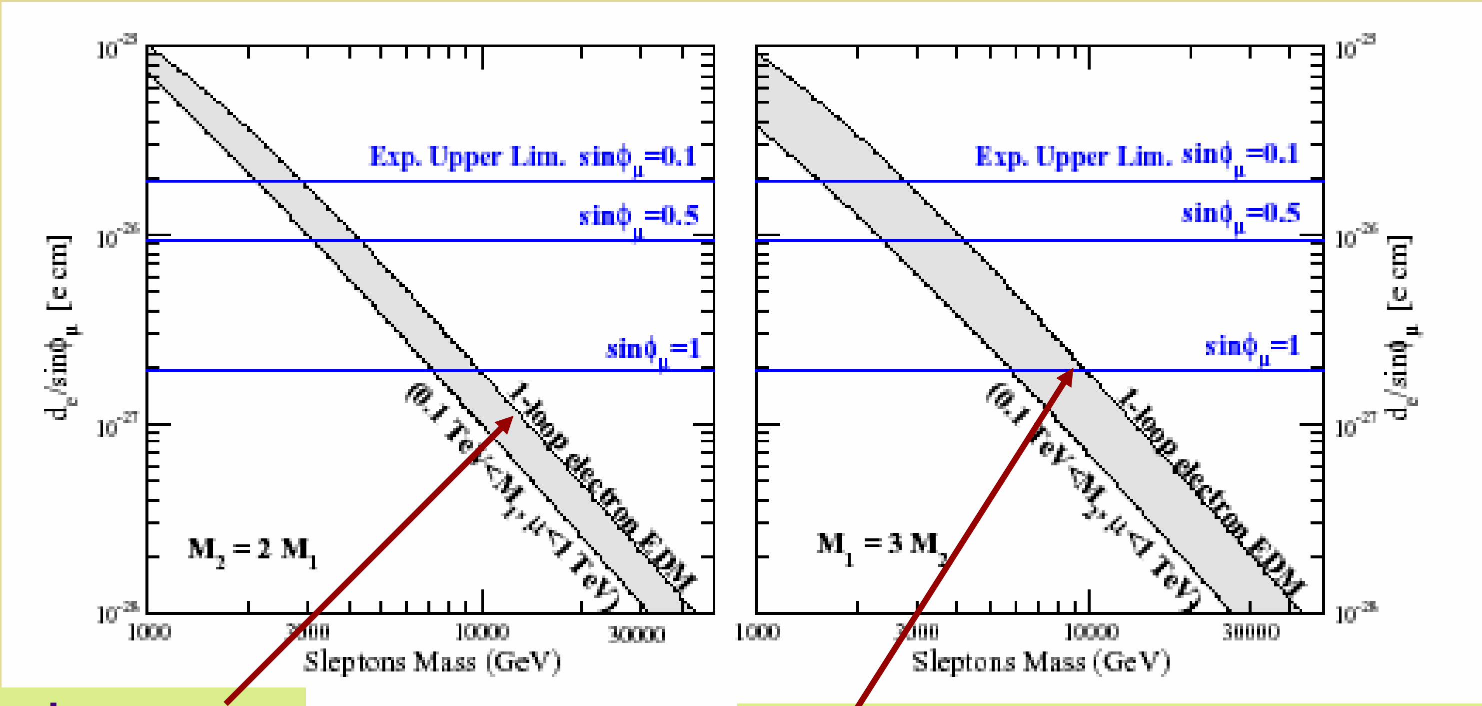
$O(\alpha_s)$

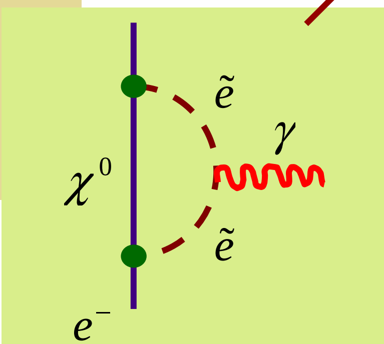
Cirigliano, Lee, R-M, Tulin

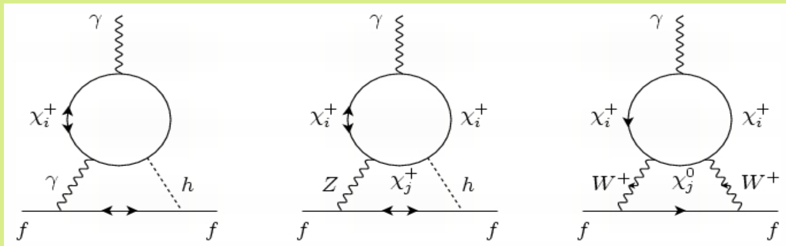
Joyce, Prokopec, Turok

EDM constraints & SUSY CPV

One-loop vs. Two-loop EDMs





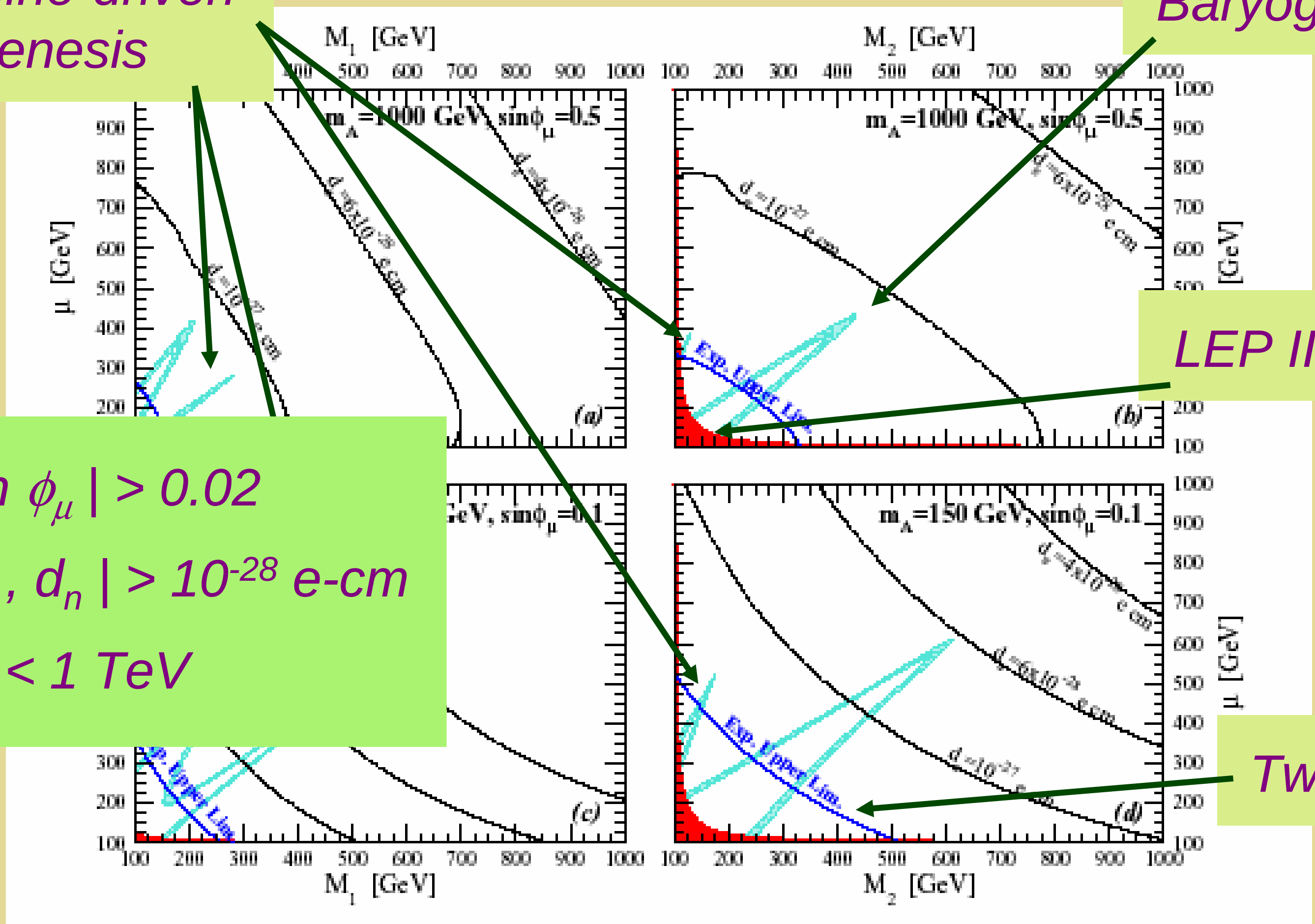


EDM constraints & SUSY CPV

DM Considerations

Neutralino-driven baryogenesis

Baryogenesis



LEP II Exclusion

$| \sin \phi_\mu | > 0.02$

$| d_e , d_n | > 10^{-28}$ e-cm

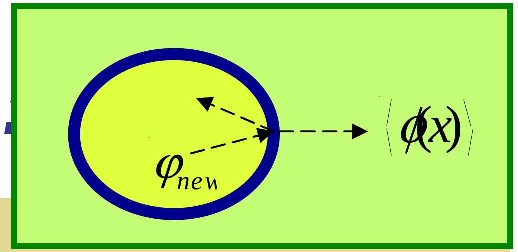
$M_\chi < 1$ TeV

Two loop d_e

SUGRA: $M_2 \sim 2M_1$

AMSB: $M_1 \sim 3M_2$

Dark Matter Considerations:



Chargino Mass Matrix

$$M_C = \begin{pmatrix} M_2 & m_W \sqrt{2} \cos\beta \\ m_W \sqrt{2} \sin\beta & \mu \end{pmatrix}$$

$$m_W \sqrt{2}\cos\beta \rightarrow \frac{g\, v_d(x)}{\sqrt{2}} \qquad m_W \sqrt{2}\sin\beta \rightarrow \frac{g\, v_u(x)}{\sqrt{2}}$$

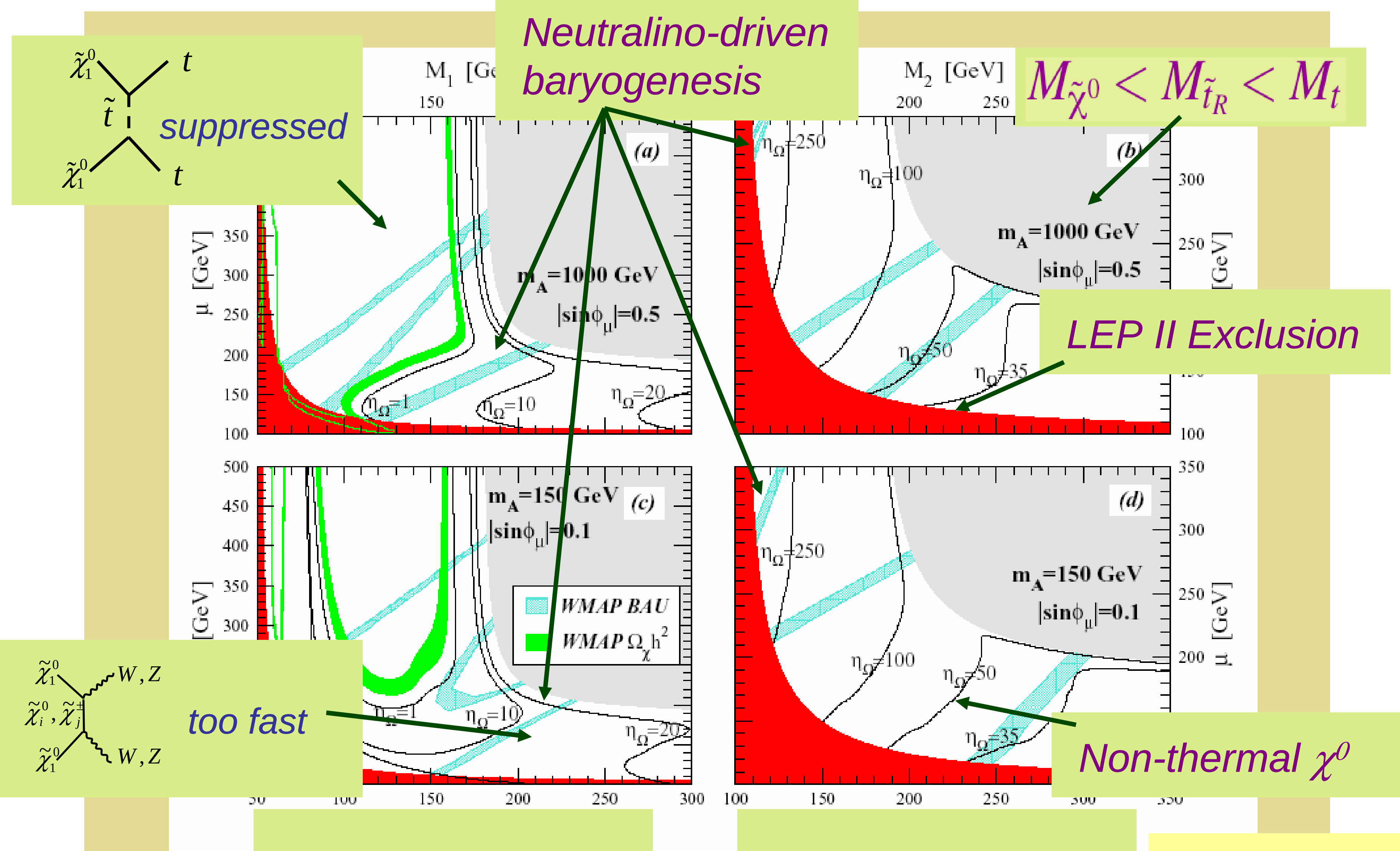
$T \sim T_{EW}$: scattering of $\widetilde{H}, \widetilde{W}$ from background field

$T \ll T_{EW}$: mixing of $\widetilde{H}, \widetilde{W}$ to $\widetilde{\chi}^{+}, \widetilde{\chi}^{0}$

Neutralino Mass Matrix

$$M_N = \begin{pmatrix} M_1 & 0 & -m_Z \cos\beta \sin\theta_W & m_Z \cos\beta \cos\theta_W \\ 0 & M_2 & m_Z \sin\beta \sin\theta_W & -m_Z \sin\beta \sin\theta_W \\ -m_Z \cos\beta \sin\theta_W & m_Z \cos\beta \cos\theta_W & 0 & -\mu \\ m_Z \sin\beta \sin\theta_W & -m_Z \sin\beta \sin\theta_W & -\mu & 0 \end{pmatrix}$$

Dark Matter: Relic Abundance

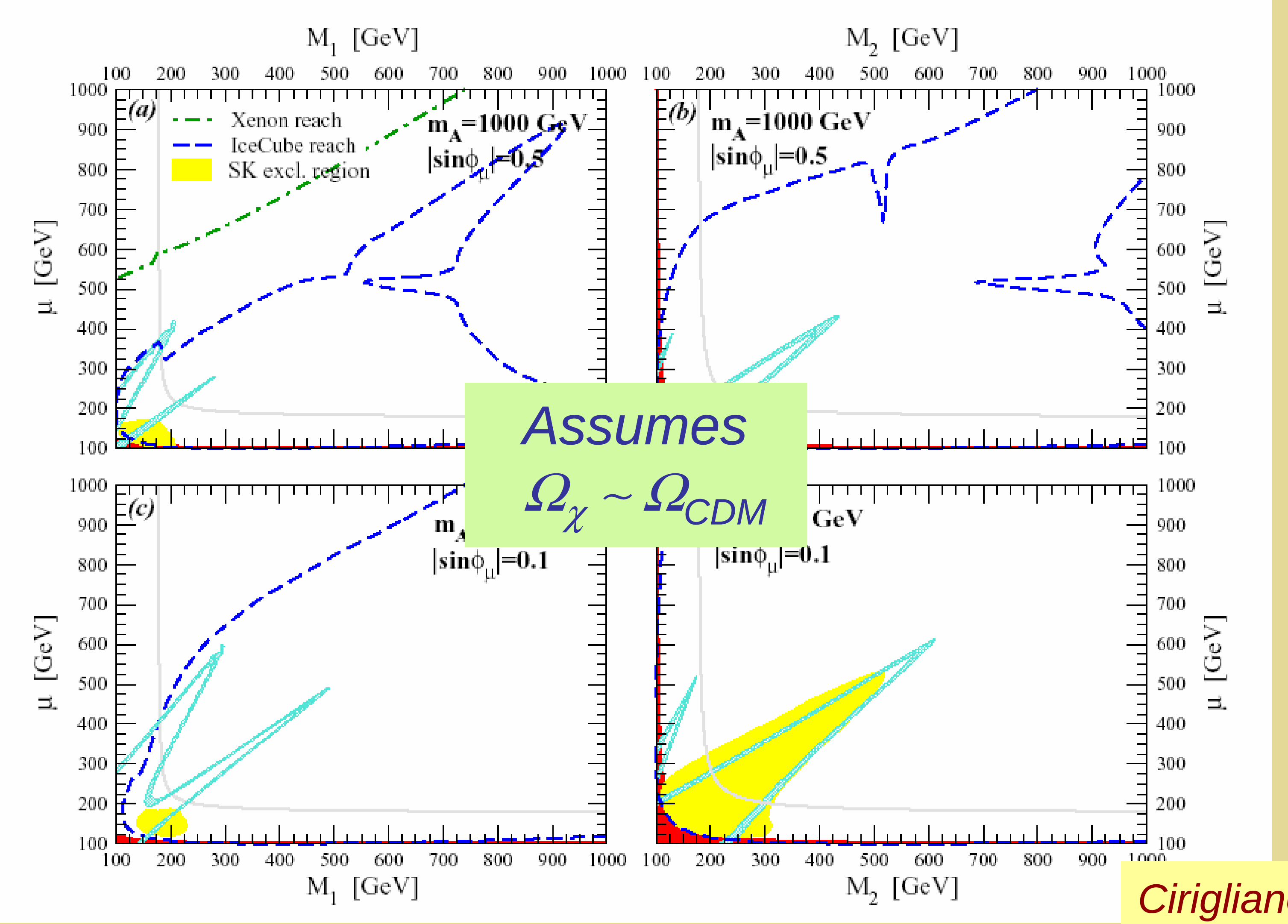


SUGRA: $M_2 \sim 2M_1$

AMSB: $M_1 \sim 3M_2$

Cirigliano, Profumo, R-M

Dark Matter: Future Experiments

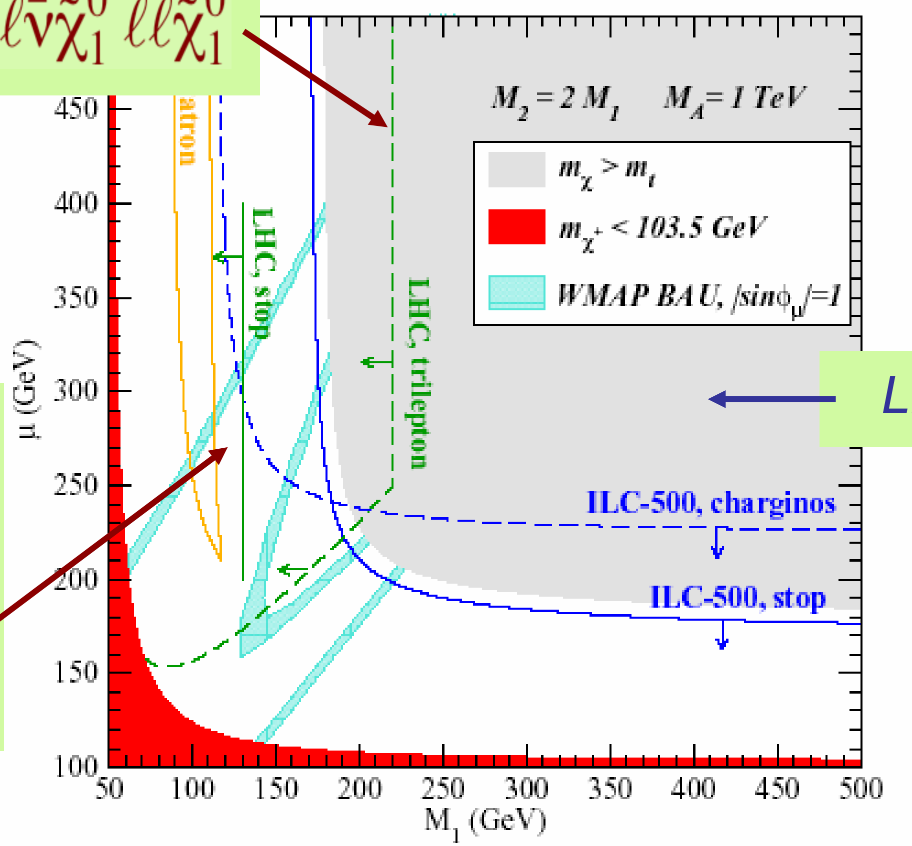


Assumes $\Omega_\chi \sim \Omega_{CDM}$

Cirigliano, Profumo, R-M

Y_B, EDMs, Dark Matter & Colliders

$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \ell\bar{\nu}\tilde{\chi}_1^0\ \bar{\ell}\ell\tilde{\chi}_1^0$$



Light Stop

$$\tilde{g}\tilde{g} \rightarrow \tilde{t}_1^* t\, \tilde{t}_1^* t$$

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$$

$$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$$

Extending the Higgs Sector

$$W = (\mu + \lambda S) H_u H_d + \alpha S + \frac{\kappa}{3} S^3$$

$$+ \mathcal{L}_{soft}$$

Implications

- *Strong 1st order EWPT w/o light stop*
- *New sources of CPV & relaxation*
- *Light singlet Higgs*
- *Singlino CDM….*

Conclusions

- *Explaining the origin of matter remains an important task at the interface of particle physics, nuclear (hadronic) physics, and cosmology*
- *CP-violation beyond that of the SM is needed to provide such an explanation*
- *Recent theoretical developments in baryogenesis are putting baryon asymmetry computations on firmer ground*
- *New EDM and dark matter searches -- together with precision electroweak and collider studies (especially the ILC) -- will provide complementary and essential tests of matter production at the electroweak scale*